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RESEARCH MEMORANDUM

COMPONENT PERFORMANCE INVESTIGATION OF J71 EXPERIMENTAL TURBINE

VI - EFFECT OF FIRST-STATOR ADJUSTMENT; OVER-ALL PERFORMANCE OF J71-97 TURBINE WITH 70-PERCENT-DESIGN-STATOR AREA

By Harold J. Schum, Donald A. Petrash, and Elmer H. Davison

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SUMMARY

The effect of first-stator area changes on the over-all component performance of the J71-97 experimental turbine is being investigated. The performance of this turbine equipped with first-stator areas nominally 97 and 132 percent of design has been reported previously. The performance of this same turbine with the first-stator area reduced to 70 percent of design by reorienting the stagger angle of the design blade profiles is presented herein and compared with that obtained for the two previously investigated turbine configurations.

The subject turbine with the 70-percent first-stator area obtained a maximum efficiency of 0.873 at 130 percent of equivalent design speed and an equivalent shaft work of 43.5 Btu per pound. This maximum efficiency compares with 0.869 for the 132-percent turbine and 0.891 for the 97-percent turbine. A higher level of work output was obtained with the 70-percent turbine, however. The first stator of this turbine choked at and above a rating total-pressure ratio of about 3.4 for all speeds investigated at a weight flow of 32.28 pounds per second. The first-stage rotor also choked at the hub at a pressure ratio of approximately 4.2. A static-pressure rise (negative reaction) occurred across the hub of the first-stage rotor at the equivalent design speed and over the entire range of rating total-pressure ratio investigated. An approximately proportional weight-flow decrease was observed as the first-stage stator area was decreased from 95.6 to 70 percent of design; an increase in area from 95.6 to 132 percent of design resulted in less than a proportional air-weight-flow change. From a compressor-turbine match-point analysis, based on the experimental data and an assumed mode of engine operation during which the compressor is maintained at constant equivalent design conditions, the 70-percent-area turbine produced insufficient work output to drive the compressor.

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INTRODUCTION

As part of a general study of high-work-output low-blade-speed multistage turbines, the NACA Lewis laboratory is currently investigating the effect of first-stage stator adjustment on the over-all component performance characteristics of the J71-97 experimental three-stage turbine. Results for two turbine configurations, one with a first-stator throat area of approximately 97 percent of the design value and the other with a first-stator throat area of 132 percent of design, are reported in references 1 and 2, respectively. 4057 The increase in first-stator throat area resulted in approximately a 13.6-percent increase in the choking equivalent weight flow and a decrease in the maximum efficiency obtained from 0.891 to 0.869.

In order to determine the effect on over-all turbine performance of reducing the first-stage stator throat area of the experimental three-stage turbine, the unit was modified by installing a first-stage stator with a throat area 70 percent that of design. This report presents the over-all component performance of this modified turbine, hereinafter called the J71-70 turbine or simply the 70-percent turbine. This turbine was investigated similarly to the 97-percent and the 132-percent turbine configurations, with equivalent cold-air inlet conditions. The results for all three turbine configurations are compared herein. Also included is a discussion of compressor and turbine match-point characteristics for a particular mode of engine operation.

SYMBOLS

The following symbols are used in this report:

E enthalpy drop based on torque measurements, Btu/lb

g acceleration due to gravity, 32.174 ft/sec^2

N rotational speed, rpm

p pressure, in. Hg abs

p_x' rating total pressure, static pressure plus velocity pressure corresponding to axial component of velocity, in. Hg abs

R gas constant, 53.4 ft-lb/(lb)($^{\circ}$R)

T temperature, $^{\circ}$R

w weight flow, lb/sec

$\frac{wN}{60\delta}\,\varepsilon$ weight-flow parameter based on product of equivalent weight flow and equivalent rotor speed

γ ratio of specific heats

δ ratio of inlet-air pressure to NACA standard sea-level pressure, $p_0'/29.92$ in. Hg abs

ε function of γ, $$\frac{\gamma_{sl}}{\gamma_e}\left[\frac{\left(\frac{\gamma_e + 1}{2}\right)^{\frac{\gamma_e}{\gamma_e - 1}}}{\left(\frac{\gamma_{sl} + 1}{2}\right)^{\frac{\gamma_{sl}}{\gamma_{sl} - 1}}}\right]$$

η_i brake internal efficiency, ratio of actual turbine work based on torque measurements to ideal turbine work based on inlet total pressure p_0' and outlet rating total pressure $p_{x,7}'$

θ_{cr} squared ratio of critical velocity at NACA standard sea-level temperature of 518.7° R, $$\frac{\frac{2\gamma}{\gamma + 1}\,gRT_0'}{\frac{2\gamma_{sl}}{\gamma_{sl} + 1}\,gRT_{sl}}$$

τ torque, ft-lb

Subscripts:

e engine operating conditions

sl NACA standard sea-level conditions

x axial

0,1,2,
3,4,5, measuring stations (see fig. 2)
6,7

Superscript:

' total or stagnation state

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APPARATUS AND INSTRUMENTATION

The investigation of the 70-percent turbine was conducted with the same turbine test facility and installation as were used for the 97-percent and 132-percent turbines (refs. 1 and 2). A photograph of the over-all setup is presented in figure 1. For this investigation the first-stage stator of the experimental J71-97 three-stage turbine was replaced with one having a stator throat area 70 percent that of design. This change in area was effected in the same manner as was used to obtain the 132-percent-area first stator; that is, the stagger angle of the design blade profiles was oriented to the angle required to result in the desired throat area. For the 70-percent turbine investigated herein, the first-stator chord angle was increased approximately $8\frac{1}{2}^{\circ}$ from axial and from the design setting. This change compares with some $9\frac{1}{2}^{\circ}$ decrease in the design blade-chord angle for the 132-percent turbine (ref. 2). 4057

A schematic diagram of the turbine showing axial and circumferential locations of the instrumentation is presented in figure 2. Briefly, measurements of total pressure, wall static pressure, and total temperature were taken at the turbine inlet (station 0) and at the turbine outlet (station 7). In addition, wall static taps were installed ahead of each row of blades.

METHODS AND PROCEDURE

The turbine was operated with a nominal measured inlet pressure p_0' of 35 inches of mercury absolute and an inlet temperature T_0' of 700° R for equivalent speeds of 20, 40, 60, 70, 80, 90, 100, 110, 120, and 130 percent of the equivalent design speed $N/\sqrt{\theta_{cr}}$. A range of rating total-pressure ratio $p_0'/p_{x,7}'$ from 1.4 to 6.4 was investigated. The method used to convert turbine test conditions to equivalent operating conditions based on NACA standard sea-level conditions (29.92 in. Hg abs and 518.7° R) is given in reference 3. Both the equivalent work output E/θ_{cr} and brake internal efficiency η_i values presented herein are based on measured values of torque, weight flow, and speed. The equivalent weight flow $\frac{w\sqrt{\theta_{cr}}}{\delta}\varepsilon$ has been corrected for the fuel addition required to maintain a turbine-inlet temperature T_0' of about 700° R.

The brake internal efficiency is based on the calculated turbine-outlet pressure $p_{x,7}'$. This calculated value of turbine-outlet total pressure charges the turbine for the energy of the tangential component of velocity. The outlet total pressure was calculated from the energy equation and continuity by using the known annulus area at the measuring station and the measured values of weight flow, static pressure, total pressure, and total temperature.

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Based on a mode of engine operation in which the compressor was assumed to operate at constant design equivalent conditions, a turbine match-point analysis was evolved for the 132-percent-area turbine in reference 2. The calculations required for this analysis were extended somewhat for the subject 70-percent turbine, and the match-point performance characteristics of this turbine are compared with those of the 97-percent turbine (ref. 1) and the 132-percent turbine (ref. 2).

RESULTS AND DISCUSSION

Over-All Performance

Figure 3 presents the over-all performance of the 70-percent turbine as a plot of equivalent shaft work E/θ_{cr} as a function of the flow parameter $(wN/60\delta)\varepsilon$ for constant values of equivalent rotor speed $N/\sqrt{\theta_{cr}}$ and rating total-pressure ratio $p_0'/p_{x,7}'$. Also shown are contours of constant values of brake internal efficiency η_i, calculated from the observed torque readings and the rating total-pressure ratios. Comparison of this turbine performance map (fig. 3) with those for the 97-percent turbine (ref. 1) and 132-percent turbine (ref. 2) shows that a considerably higher level of equivalent shaft work was available with the 70-percent turbine. The maximum efficiency obtained was 0.873, occurring at 130 percent of equivalent design speed and a turbine work output of 43.5 Btu per pound. This maximum efficiency compares closely with 0.869 for the 132-percent turbine (ref. 2) and 0.891 for the 97-percent turbine (ref. 1).

The variation of equivalent torque with over-all rating total-pressure ratio for the various equivalent rotor speeds investigated is presented in figure 4. For all speeds, the equivalent torque continually increased as the over-all pressure ratio increased, indicating that limiting loading was not attained within the range of pressure ratio imposed across the turbine. The same conditions prevailed in the investigations of references 1 and 2. The pressure-ratio range for all three turbines was limited by the air and exhaust facilities available to the turbine. From the slope of the torque curves (fig. 4), however, it can be noted that, at the higher speeds and pressure ratios, only a slight increase in torque would result if higher pressure ratios had been available.

Choking Characteristics

The variation of the equivalent weight flow $\frac{w\sqrt{\theta_{cr}}}{\delta}\epsilon$ with over-all rating total-pressure ratio for the 70-percent turbine is presented in figure 5 for the various equivalent rotor speeds investigated. These data show that the first-stage stator is choked at and above a pressure ratio of about 3.4, because a constant equivalent weight flow was obtained for all rotor speeds. The observed choking value of equivalent weight flow was 32.28 pounds per second. This choking equivalent weight flow for the 70-percent turbine is shown in figure 6, along with the corresponding first-stator throat area. If the first stator controls the weight flow through the turbine, then the choking equivalent weight flow should increase proportionately with an increase in stator throat area, assuming that no change in flow coefficients occurs. This choking-flow relationship is shown in figure 6 as a straight line constructed through the data point obtained for the 70-percent turbine. Also shown in figure 6 are the experimental ranges of choking weight flow for the 97-percent turbine (ref. 1) and the 132-percent turbine (ref. 2), plotted against their measured first-stator throat areas. It should be stated that the 97-percent turbine was fabricated with stator areas nominally 97 percent of their design values. However, because of manufacturing tolerances, this first-stator area was actually 95.6 percent that of design. In both the 97-percent and the 132-percent turbine configurations, choking occurred downstream of the first stator, resulting in a range of choking equivalent weight flows with speed as shown in figure 6. It will be noted, however, that, even though the first stator did not choke for the 97-percent turbine, the range of weight flow approached the theoretical equivalent weight flow that would result if the first stator were choked. This indicates that the first stator of the 97-percent turbine was very nearly choked. That the choking weight-flow range for the 132-percent turbine was far removed from the first-stator choking curve indicates that some downstream blade row controlled the weight flow through the turbine. These data indicate an approximately proportional weight-flow increase as the first-stage stator area was increased from 70 to 95.6 percent of design; a further increase in area from 95.6 to 132 percent of design resulted in less than a proportional air-weight-flow change.

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As stated previously, the first stator was choked over most of the pressure-ratio range investigated. It was considered of interest, then, to determine whether any other blade row or rows also choked. Accordingly, the arithmetic averages of the hub static pressures at each measuring station for all measuring stations are presented in figure 7 for a range of over-all rating total-pressure ratio at the equivalent design speed. These static pressures were divided by the inlet total pressure p_0' in order to eliminate the small inlet total-pressure variations encountered in the tests. A blade row is choked when the static pressure at the inlet to a particular blade row remains constant while the static pressure at the outlet of the same blade row decreases as the over-all rating total-pressure ratio across the turbine is increased. In addition to the choking of the first stator, as discussed previously, figure 7 indicates the first rotor also chokes at a rating pressure ratio of about 4.2, since the static pressure at measuring station 2 (upstream of the first rotor) is constant, whereas at station 3 (downstream of the first rotor) the static pressure continually decreases until a pressure ratio of about 5.7 is reached. It will be noted that all measuring stations have a zero slope at and above this pressure ratio, except for station 7, which shows a continued static-pressure decrease. This indicates the third rotor choked at a turbine rating pressure ratio of about 5.7. It is conceivable that intermediate blade rows choke simultaneously with the third rotor, but this cannot be definitely established from static-pressure plots such as figure 7.

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Examination of figure 7 shows the hub static- to total-pressure ratio at measuring station 2 (downstream of the first stator) obtained a constant value of 0.34 at a rating total-pressure ratio of about 4.2 and above. This value of static- to total-pressure ratio corresponds to an absolute Mach number of 1.34, assuming no total-pressure drop across the stator, compared with the design Mach number of 0.767. Figure 7 also reveals a static-pressure rise (negative reaction) across the hub of the first-rotor row of blades over the entire range of over-all rating total-pressure ratio investigated.

Matching Characteristics

Changes in first-stator area result in changes in the turbine weight flow, as shown in figure 6; hence, engine operating conditions are also changed. In reference 2, the turbine matching requirements were calculated for an engine mode of operation during which the compressor is maintained at constant equivalent design conditions. With these requirements known, the experimental performance results for the 132-percent turbine were used to determine its experimental match point. In addition, the experimental match point of the 97-percent turbine was also determined. Comparison of the efficiency values for these two turbine configurations at their respective experimental match points indicated that the efficiency decreased only 1 point, from 0.87 to 0.86, as the first-stator area was increased. Both of these efficiency values were in the high-efficiency regions of their respective turbine performance maps (refs. 1 and 2).

In order to determine the corresponding experimental match point for the 70-percent turbine, the calculations and curves of reference 2 were extended. The turbine match point was then determined, again based on a mode of engine operation during which the compressor was maintained at constant equivalent design conditions. These results are shown in figure 8.

In determining the turbine match point for the 70-percent turbine, it was found that the equivalent design torque (3204 ft-lb) was not obtained at any equivalent speed above 100 percent (see fig. 4). As a result, no match point for the turbine could be obtained such that the compressor could be operated at its equivalent design conditions. However, it was considered of interest to determine what the turbine equivalent work output should have been for the choking equivalent weight flow obtained, and to compare this required work output with the actual work obtained in the tests. Therefore, the choked weight flow was superimposed on figure 8. The turbine match-point equivalent speed, then, would be 124.9 percent that of design. Simultaneously, the equivalent weight flow corresponds to an engine temperature ratio of 2.67 and an equivalent-shaft-work requirement of 50.38 Btu per pound. From the tests of the 70-percent turbine, the maximum equivalent work obtained was only 44.6 Btu per pound (fig. 3), and this was obtained at a rating total-pressure ratio of 6.4 and at 130 percent of the equivalent design speed.

It is obvious, then, that this turbine with the first-stator area reduced to 70 percent of design cannot drive the compressor at constant equivalent design conditions. However, it might still be considered desirable to operate the turbine in this manner, because its maximum efficiency (0.873) is still quite high and because added flexibility in the mode of engine operation could be obtained.

SUMMARY OF RESULTS

From a cold-air investigation of the experimental J71-97 three-stage turbine with the first-stage stator area reduced to 70 percent of design by reorienting the stagger angle of the design blade profiles, the following results were obtained:

1. The maximum brake internal efficiency obtained was 0.873, occurring at 130 percent of equivalent design speed and an equivalent-shaft-work output of 43.5 Btu per pound. This efficiency compares closely with the previously obtained maximum efficiencies of 0.869 for the 132-percent turbine and 0.891 for the 97-percent turbine.

2. A higher level of equivalent shaft work was available with the 70-percent turbine than with the 97-percent and the 132-percent turbines.

3. Limiting blade loading was not reached over the range of conditions investigated, but it was closely approached at the higher speeds and rating total-pressure ratios.

4. The first-stage stator choked at and above a pressure ratio of about 3.4 for all speeds investigated. At the equivalent design speed, the first rotor choked at the hub at a pressure ratio of approximately

4.2, and the third rotor appeared to choke at a pressure ratio of about 5.7. The choking equivalent weight flow was 32.28 pounds per second.

5. An approximately proportional weight-flow decrease was observed as the first-stator area was decreased from 95.6 to 70 percent of design; an increase in area from 95.6 to 132 percent of design resulted in less than a proportional air-weight-flow change.

6. A static-pressure rise (negative reaction) occurred across the hub of the first rotor at the equivalent design speed and over the entire range of rating total-pressure ratio investigated.

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7. From a turbine match-point analysis, based on the experimental data and an assumed engine mode of operation during which the compressor is maintained at constant equivalent design conditions, insufficient turbine work output was developed to drive the compressor.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, February 27, 1956

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2. Davison, Elmer H., Petrash, Donald A., and Schum, Harold J.: Component Performance Investigation of J71 Experimental Turbine. IV - Effect of First-Stator Adjustment; Over-All Performance of J71-97 Turbine with 132-Percent-Design Stator Area. NACA RM E55H09, 1956.

3. Rebeske, John J., Jr., Berkey, William E., and Forrette, Robert E.: Over-All Performance of J35-A-23 Two-Stage Turbine. NACA RM E51E22, 1951.

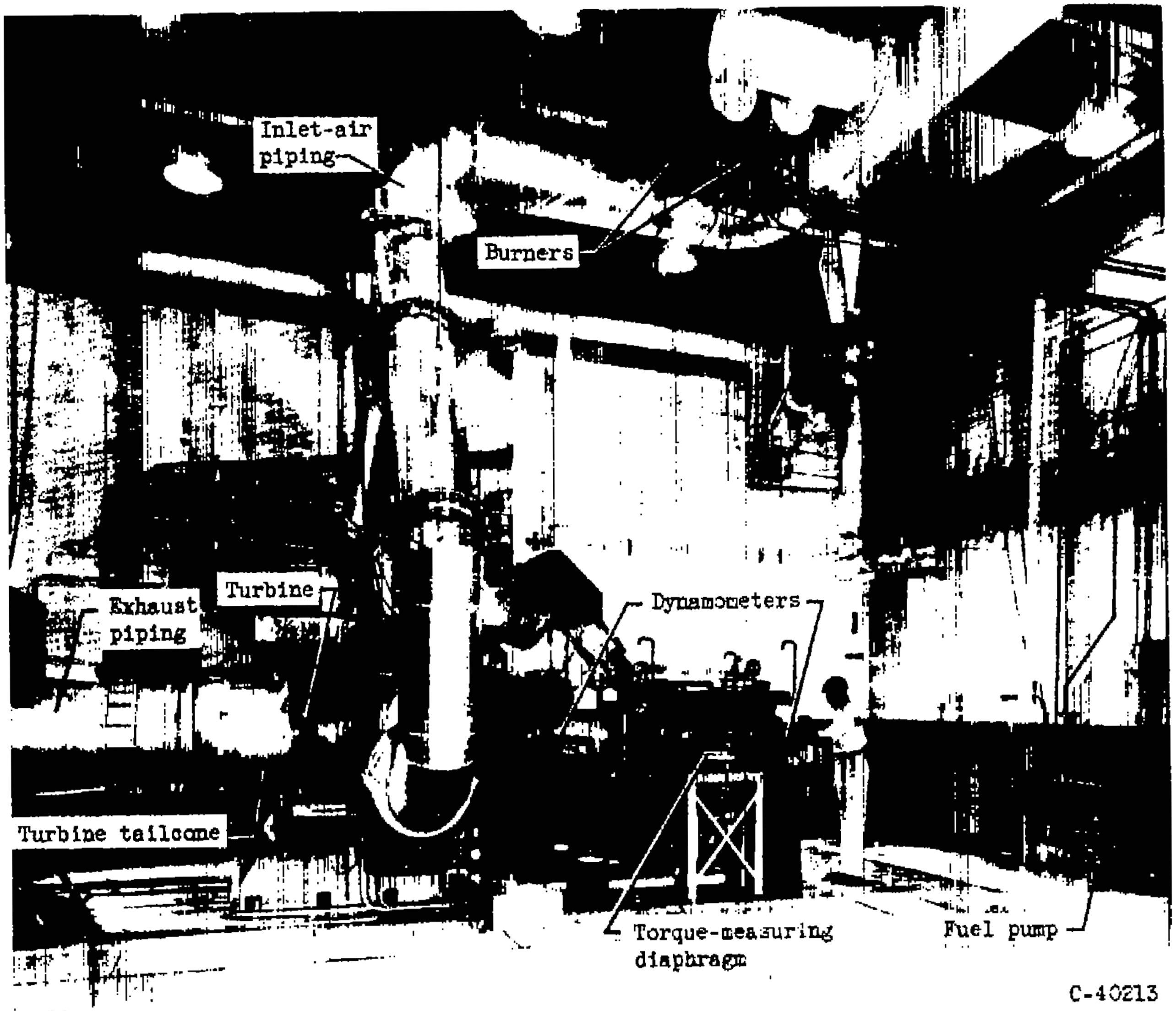

Figure 1. - Installation of experimental three-stage turbine in full-scale turbine-component test facility.

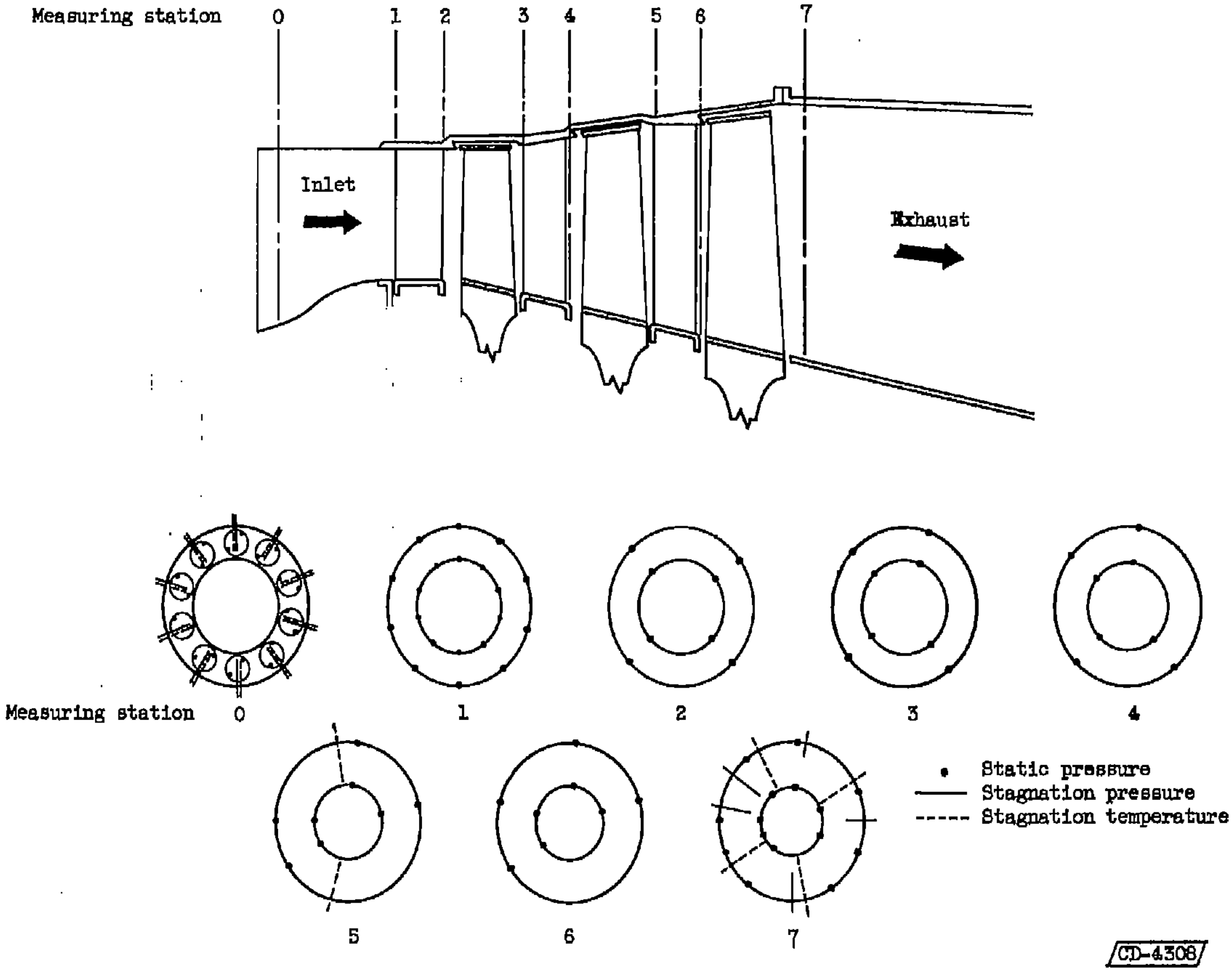

Figure 2. - Schematic diagram of experimental turbine showing instrumentation.

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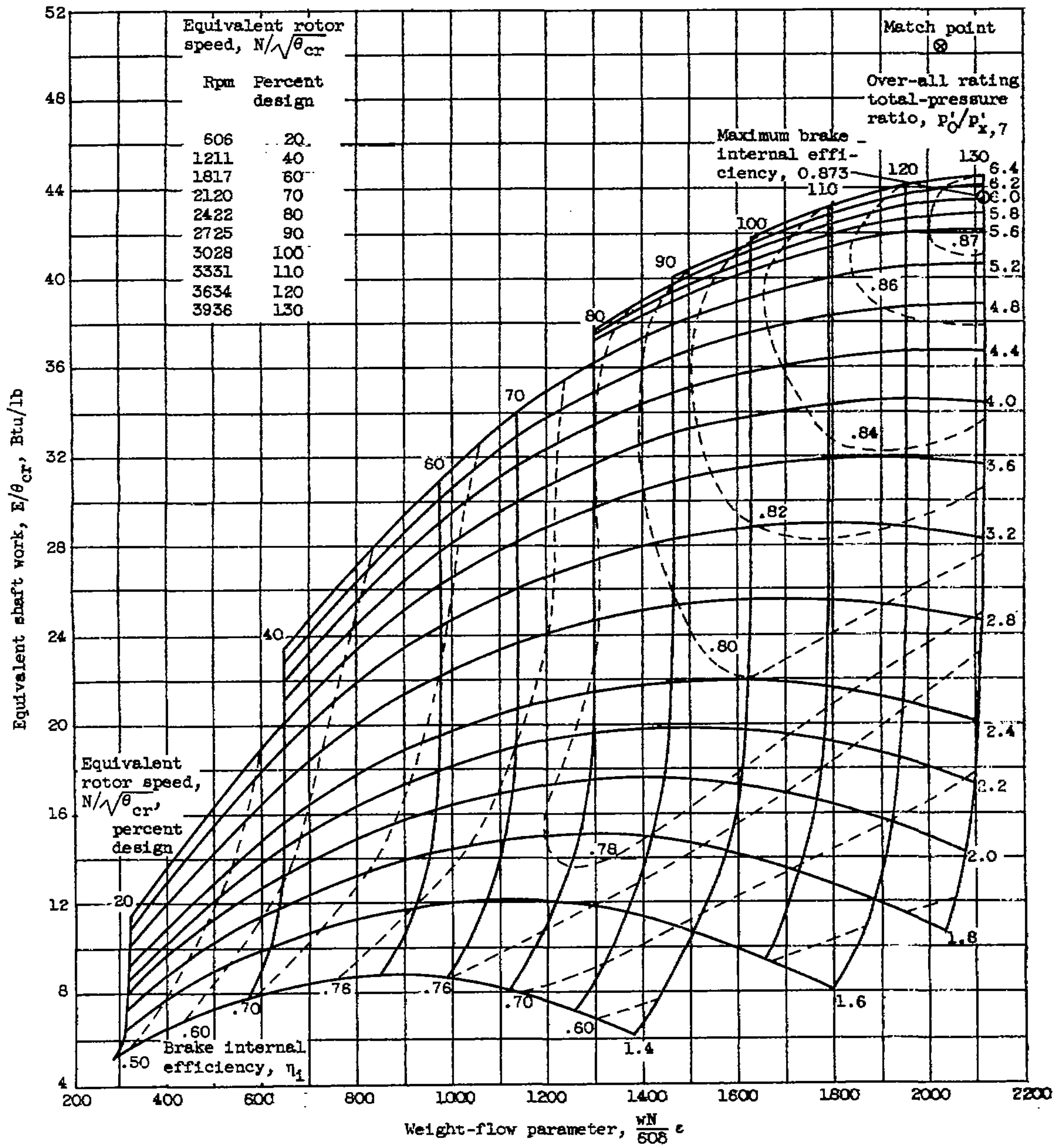

Figure 3. - Over-all performance of J71-97 turbine with 70-percent-design first-stator area. Turbine-inlet pressure, 35 inches of mercury absolute; turbine-inlet temperature, 700° R.

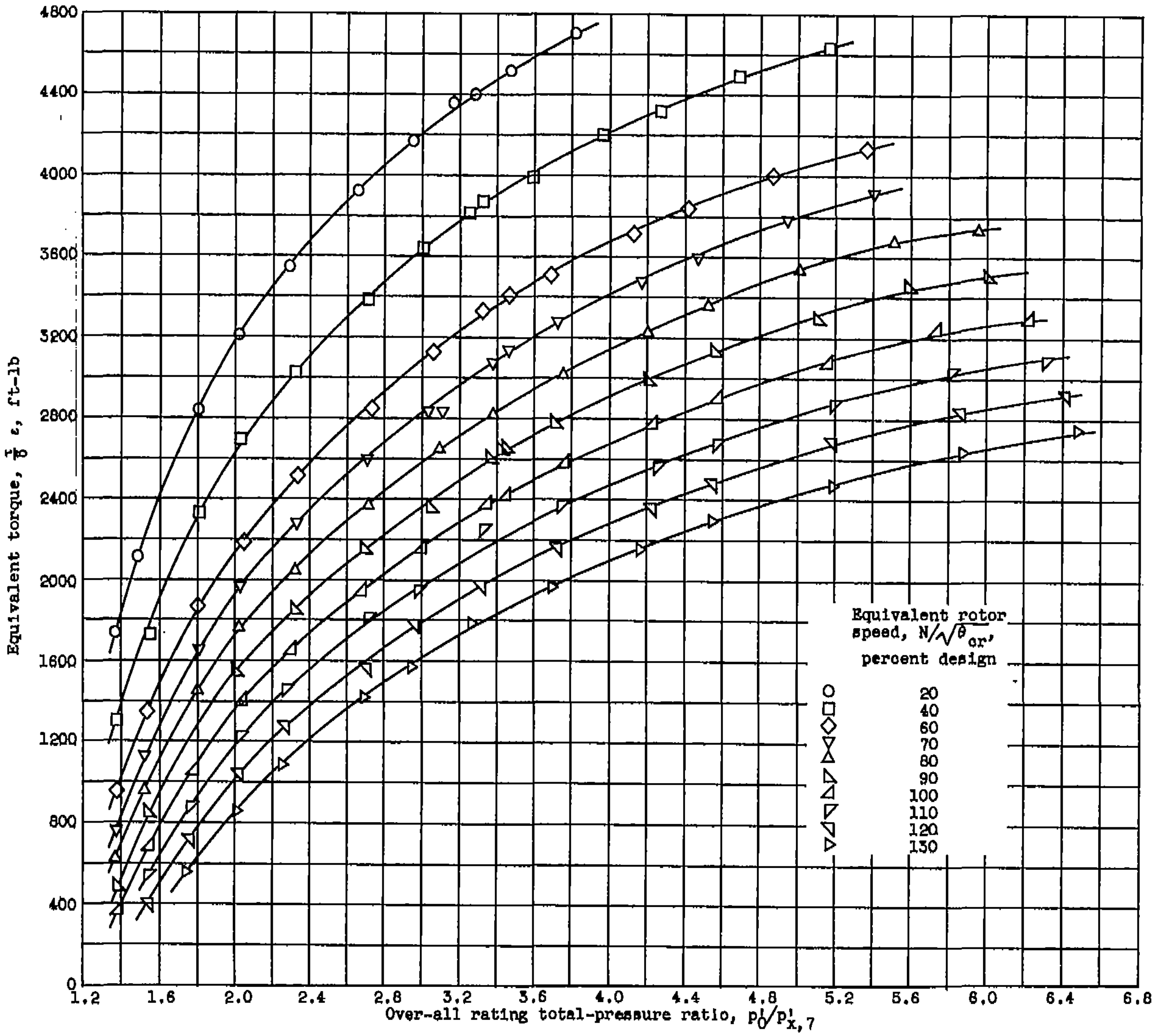

Figure 4. - Variation of equivalent torque with over-all rating total-pressure ratio for values of constant equivalent rotor speed.

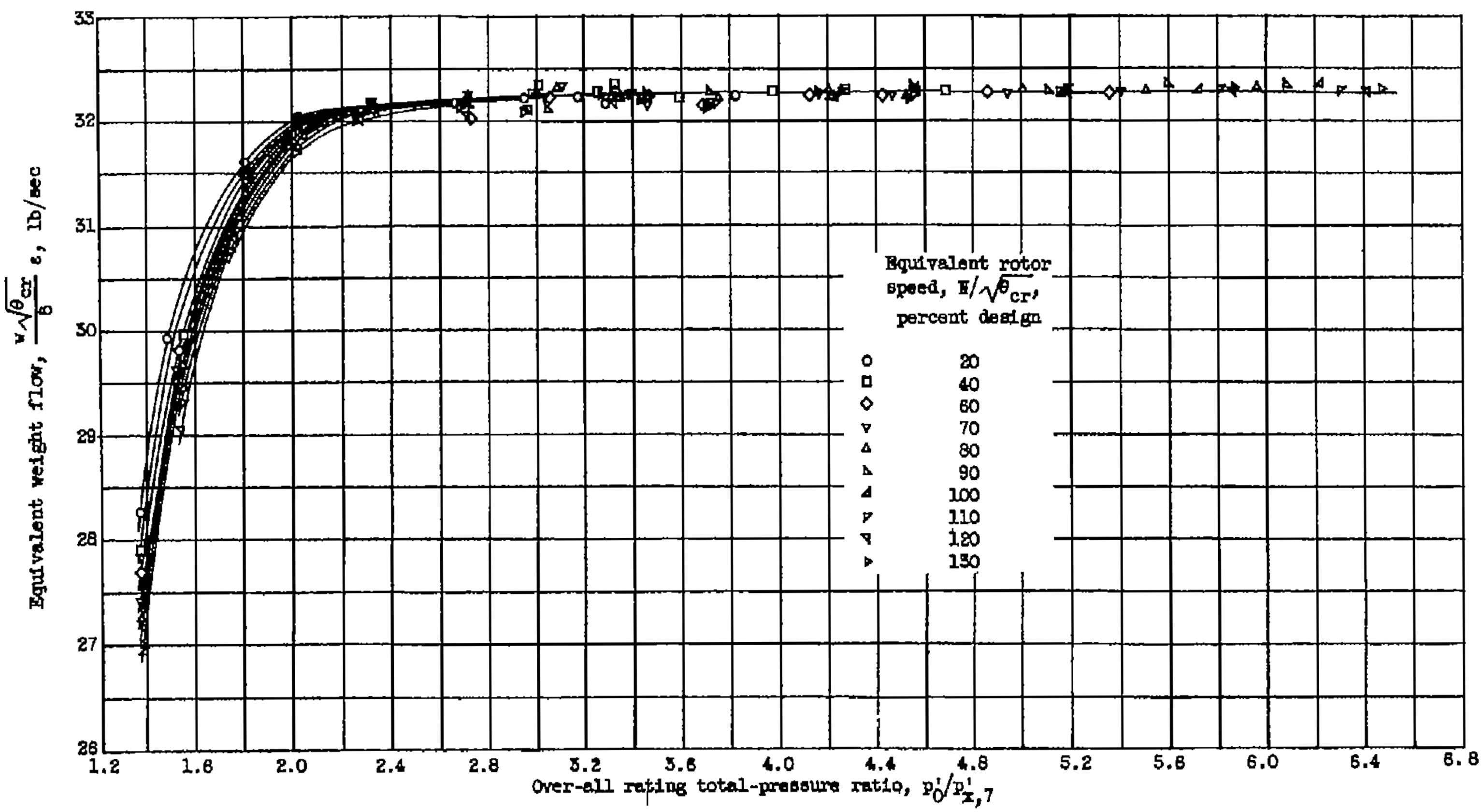

Figure 5. - Variation of equivalent weight flow with over-all rating total-pressure ratio for values of constant equivalent rotor speed.

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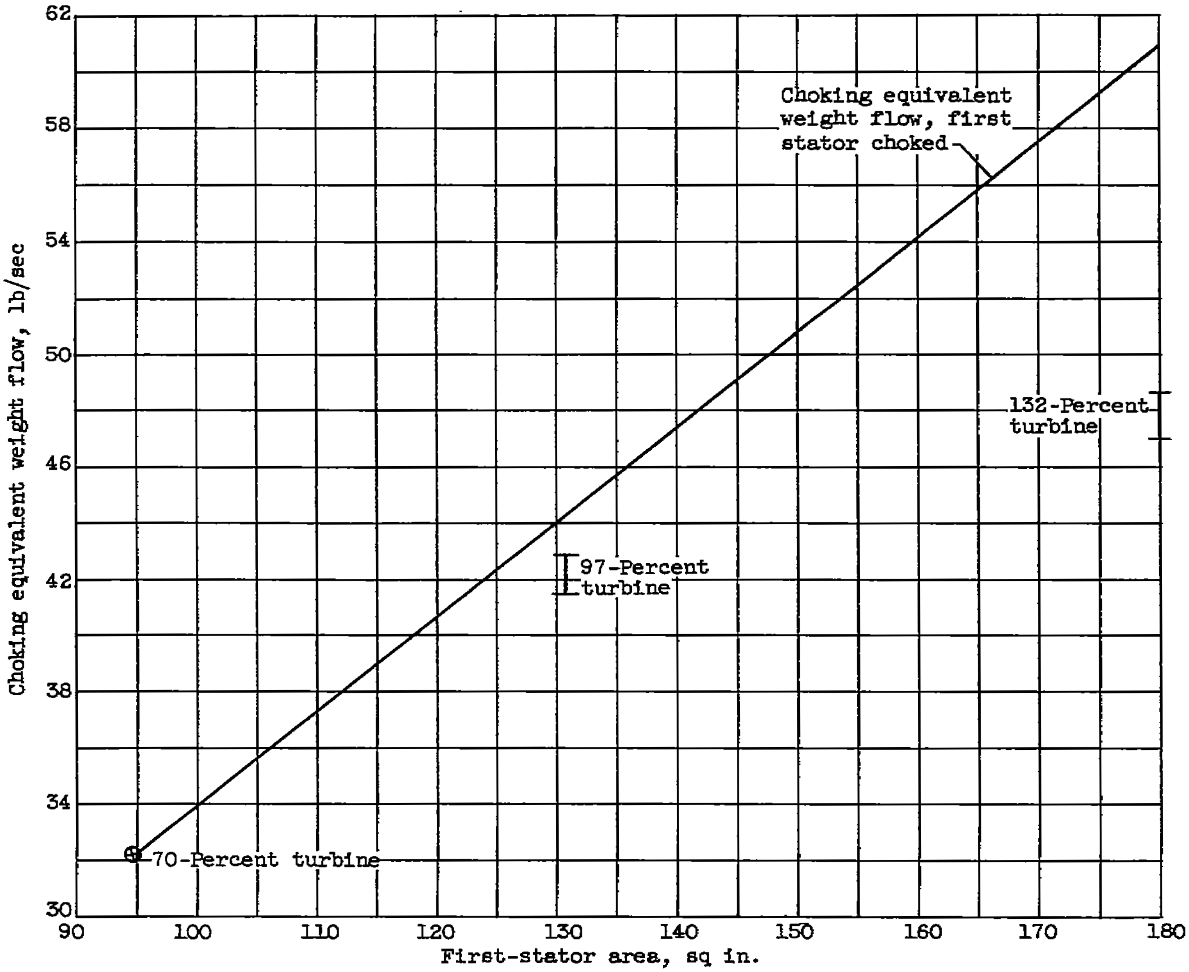

Figure 6. - Variation of choking equivalent weight flow with first-stator throat area for J71 turbine configurations.

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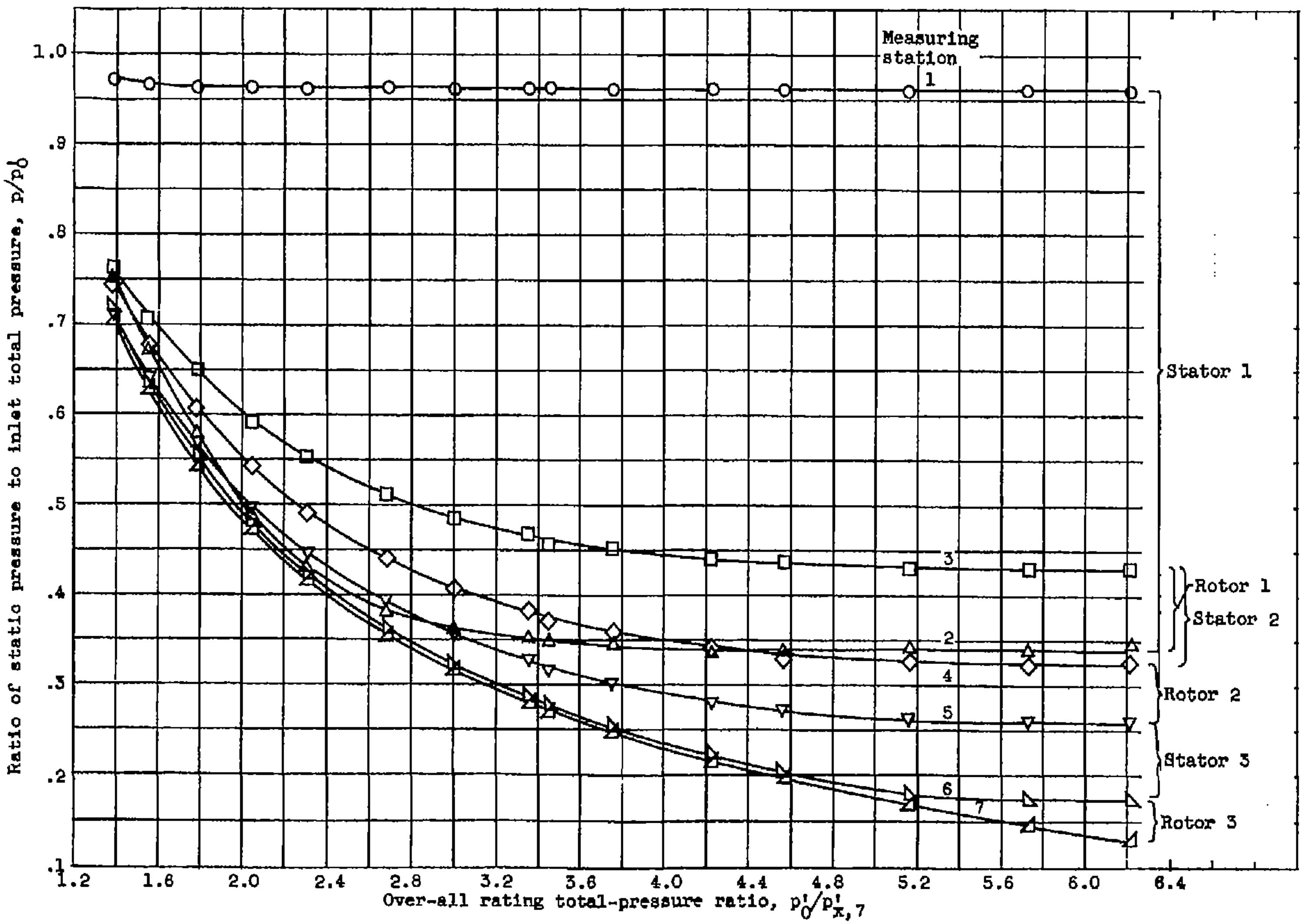

Figure 7. - Variation of static pressure at hub with over-all rating total-pressure ratio at different measuring stations for equivalent design speed.

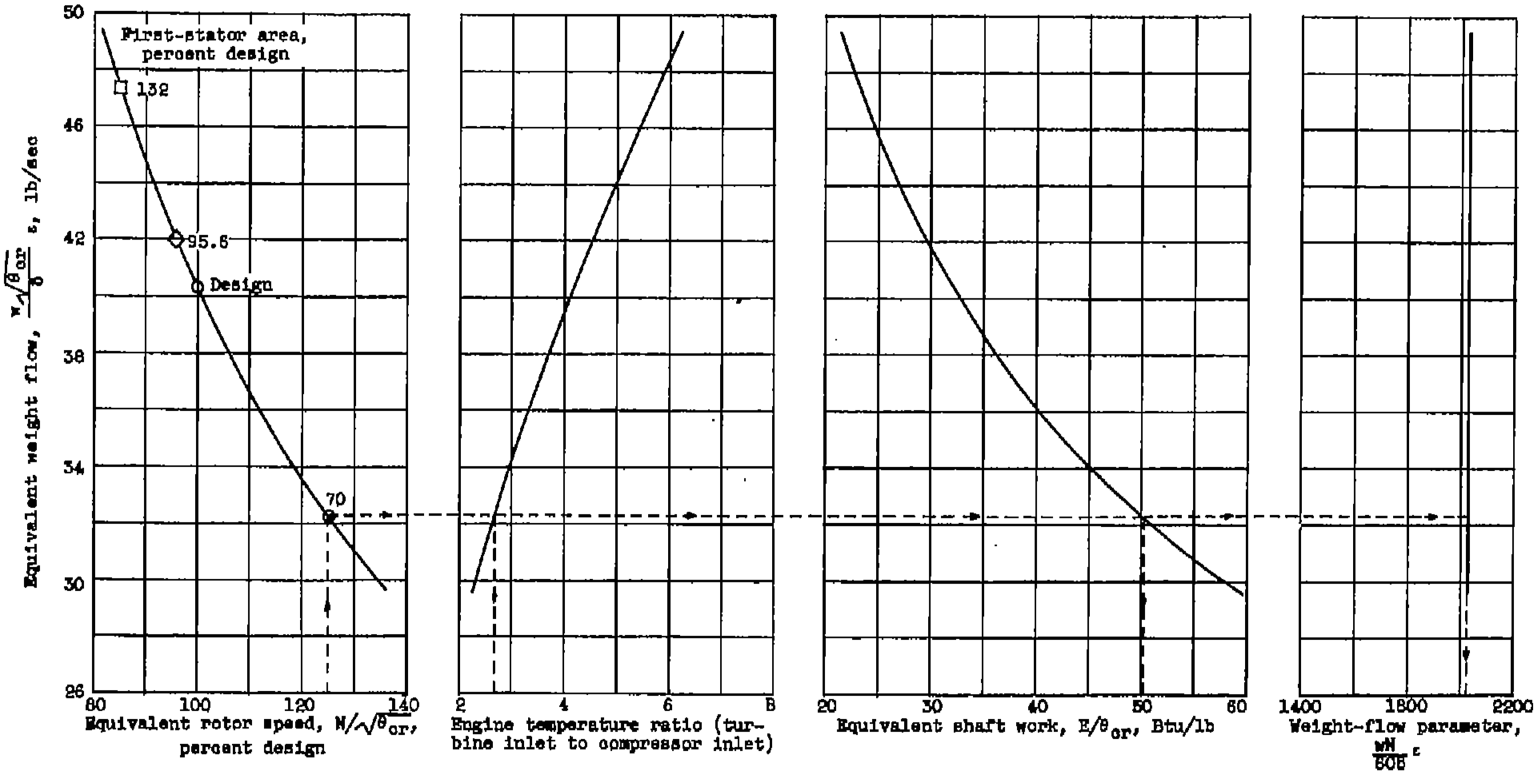

Figure 8. - Curves for determining required turbine operating conditions for maintaining compressor at constant equivalent design conditions.

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